WATER RESOURCES OF BORREGO VALLEY AND VICINITY, SAN DIEGO COUNTY, CALIFORNIA: PHASE 2--DEVELOPMENT OF A GROUND-WATER FLOW MODEL

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4199

Prepared in cooperation with the

COUNTY OF SAN DIEGO and the

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DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

The inch-pound system of units is used in this report. For those readers who prefer metric (International System) units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
foot per year (ft/yr)	0.3048	meter per year
foot per mile (ft/mi)	0.1894	meter per kilometer
gallon per minute (gal/min)	0.00006309	cubic meter per second
inch	25.4	millimeter
mile (mi)	1.609	kilometer

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

WATER RESOURCES OF BORREGO VALLEY AND VICINITY

SAN DIEGO COUNTY, CALIFORNIA

PHASE 2--DEVELOPMENT OF A GROUND-WATER FLOW MODEL

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ABSTRACT

Recharge to the three-aquifer ground-water system in Borrego Valley is due almost entirely to infiltration of intermittent streamflow and is estimated to average about 4,800 acre-feet per year. During 1946-79, net ground-water pumpage (that part of the pumpage actually consumed) ranged from about 1,700 to 13,700 acre-feet per year. The ground water was used mainly for irrigation. Because of the imbalance between recharge and pumpage, ground-water levels declined as much as 100 feet in some areas of the valley during 1945-80.

As an aid to analyzing the effects of pumping on the ground-water system, a three-dimensional finite-element ground-water flow model was developed. The model was calibrated for both steady-state (1945) and transient-state (1946-79) conditions.

For the steady-state calibration, hydraulic conductivities of the three aquifers were varied within reasonable limits to obtain an acceptable match between measured and computed hydraulic heads. During steady-state conditions, recharge from streamflow infiltration (4,800 acre-feet per year) was balanced by computed evapotranspiration (3,900 acre-feet per year) and computed subsurface outflow from the model area (930 acre-feet per year).

The volumes and distribution of net ground-water pumpage were estimated from land-use data and estimates of consumptive use for the various irrigated crops. The pumpage was assigned to the appropriate nodes in the model for each of seventeen 2-year time steps representing the transient-state period (1946-79). For transient-state calibration, the specific yields of the three aquifers were varied within reasonable limits to obtain an acceptable match between measured and computed hydraulic heads. During the transient-state period, ground-water pumpage input to the model was compensated by declines in both the computed evapotranspiration and the amount of ground water in storage.

INTRODUCTION

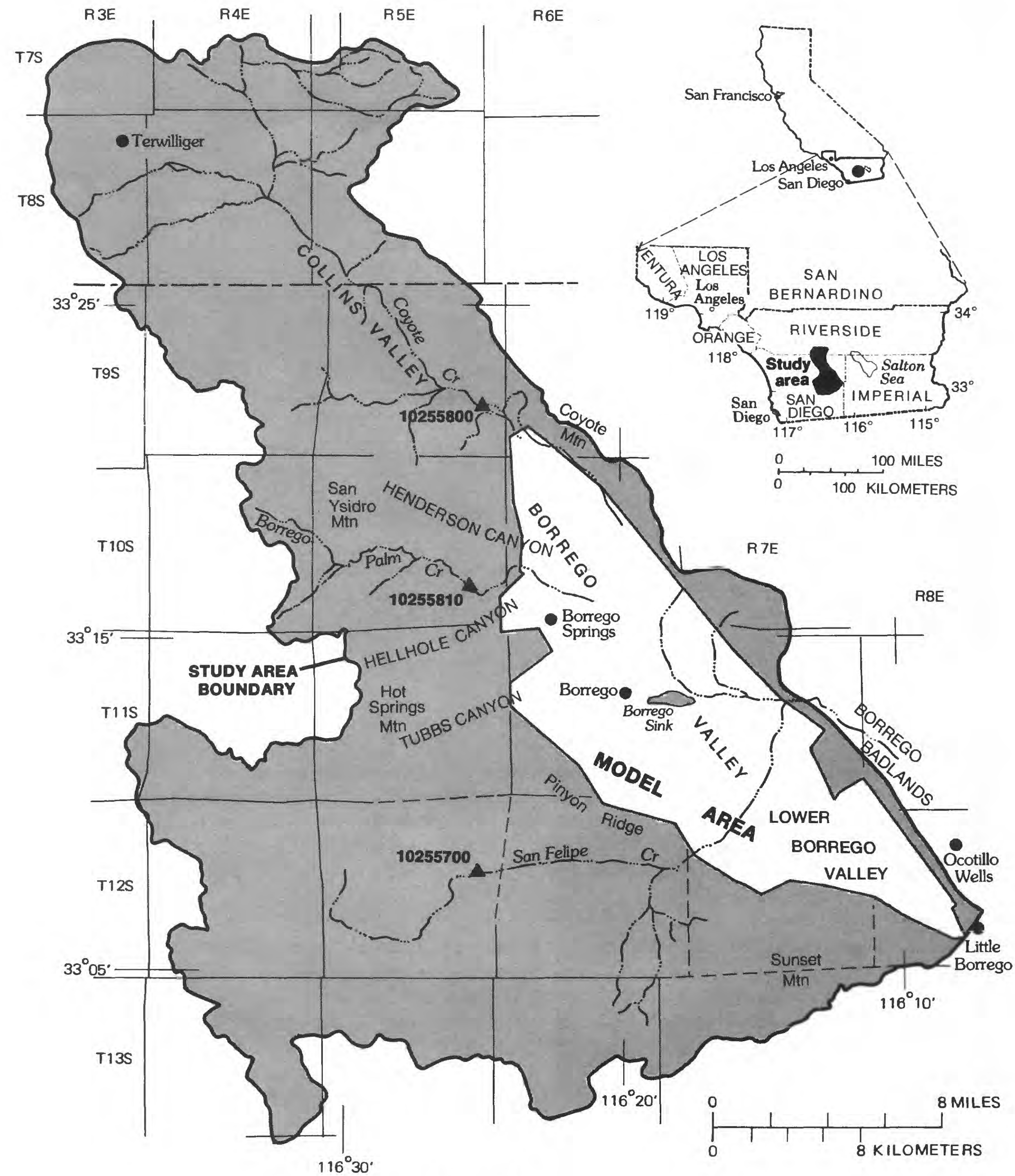
San Diego County is developing plans to assure an adequate water supply for Borrego Valley, a small valley in the northeastern part of the county about 50 miles northeast of San Diego (fig. 1). The principal source of water for the valley historically has been ground water. During 1945-80, ground-water levels declined as much as 100 feet in some areas (Moyle, 1982), mainly in response to pumping for irrigation. Since about 1950, pumpage has exceeded the long-term rate of recharge to the valley ground-water system. This stress has made careful management of available ground-water resources necessary to best meet the future water needs of Borrego Valley.

An evaluation of ground-water conditions in Borrego Valley was made by the U.S. Geological Survey in cooperation with the County of San Diego and the California Department of Water Resources. Phase 1 of the study, completed in 1982 (Moyle, 1982), concentrated on collecting basic geohydrologic information for the Borrego Valley area in order to develop a conceptual model of the ground-water system. Phase 2, described in this report, consisted of the development of a three-dimensional finite-element ground-water flow model that can be used to analyze historic and future effects of pumping on the ground-water system. Development of the digital model led to some modifications of the original conceptual model of the ground-water system (Moyle, 1982). Also, improved estimates of ground-water recharge and the historic volumes and distribution of ground-water pumpage allowed refinement of an initial digital model of the valley developed by Durbin and Berenbrock (1985).

PHYSICAL SETTING AND CLIMATE

The modeled area includes about 110 mi^2 of Borrego and Lower Borrego Valleys (fig. 1). Coyote and San Felipe Creeks are the major streams in the area, but they are dry many days each year. Borrego Valley lies at an altitude higher than that of the Salton Sea to the east, and much lower than that of Collins Valley to the northwest. The topography surrounding Borrego Valley is characterized by steep-sided mountains that range in altitude from 1,000 to 5,000 feet above sea level. Borrego Valley is bounded on the north and east by Coyote Mountain and the Borrego Badlands, on the south by Sunset Mountain and Pinyon Ridge, and on the west by a high range of mountains that includes Hot Springs and San Ysidro Mountains. San Felipe Creek forms the boundary separating Borrego Valley from Lower Borrego Valley.

Borrego Valley has an arid climate that is characterized by hot summers and cool winters. The average annual precipitation ranges from about 3 inches on the valley floor to 16 inches in the high mountains to the west (Rantz, 1969). Free-water-surface evaporation, such as from a shallow lake, ranges from 60 to 70 inches per year in Borrego Valley (National Oceanic and Atmospheric Administration, 1982).



EXPLANATION

▲ 10255700 GAGING STATION AND NUMBER

FIGURE 1. – Location of model area in Borrego and Lower Borrego Valleys.

GEOHYDROLOGY

Aquifer Characteristics

Alluvial deposits of Quaternary age and continental deposits of Quaternary and Tertiary age (fig. 2) are the main water-bearing units in Borrego Valley. The deposits are unconsolidated at land surface and become progressively more consolidated with depth. The alluvial and continental deposits are underlain by a nearly impermeable complex of igneous and metamorphic rocks of pre-Tertiary age that crops out in the mountains surrounding Borrego Valley.

On the basis of geologic, hydrologic, and geophysical information, Moyle (1982) divided the water-bearing deposits of Borrego Valley into lower, middle, and upper aquifers (fig. 3). The lower aquifer is composed primarily of partly consolidated siltstone, sandstone, and conglomerate in the lower part of the continental deposits. The lower aquifer is as much as 1,800 feet thick; however, it yields only small quantities of water to wells. The hydraulic conductivity of the lower aquifer is estimated to average 1 ft/d (Moyle, 1982). The specific yield of the aquifer probably ranges from 1 to 5 percent, and the specific storage probably averages 0.000001 per foot of aquifer.

The middle aquifer is composed primarily of moderately consolidated sand, gravel, and boulders in the upper part of the continental deposits. The aquifer is as much as 700 feet thick in the northern part of the valley (Moyle, 1982), but it thins significantly in a southeasterly direction (fig. 3). The middle aquifer yields moderate quantities of water to wells, but it is not considered a viable source of water south of San Felipe Creek because of its diminished thickness. The hydraulic conductivity of the middle aquifer is estimated to average 5 ft/d (Moyle, 1982). Specific yield of the aquifer probably ranges from 5 to 10 percent, and specific storage probably averages 0.000001 per foot of aquifer.

The upper aquifer is composed of unconsolidated sand, gravel, silt, and clay in the alluvial deposits. The upper aquifer is the principal source of ground water in Borrego Valley, and it yields as much as 2,000 gal/min to individual wells. The upper aquifer is about 600 feet thick in the northern part of Borrego Valley; however, it thins to the southeast and is only about 50 feet thick near Borrego Sink. South of San Felipe Creek in Lower Borrego Valley, the alluvial deposits are usually unsaturated. Hydraulic conductivity of the upper aquifer probably averages 50 ft/d (Moyle, 1982). The upper aquifer is unconfined, and specific yield probably ranges from 10 to 25 percent in the main water-producing zones in the aquifer.

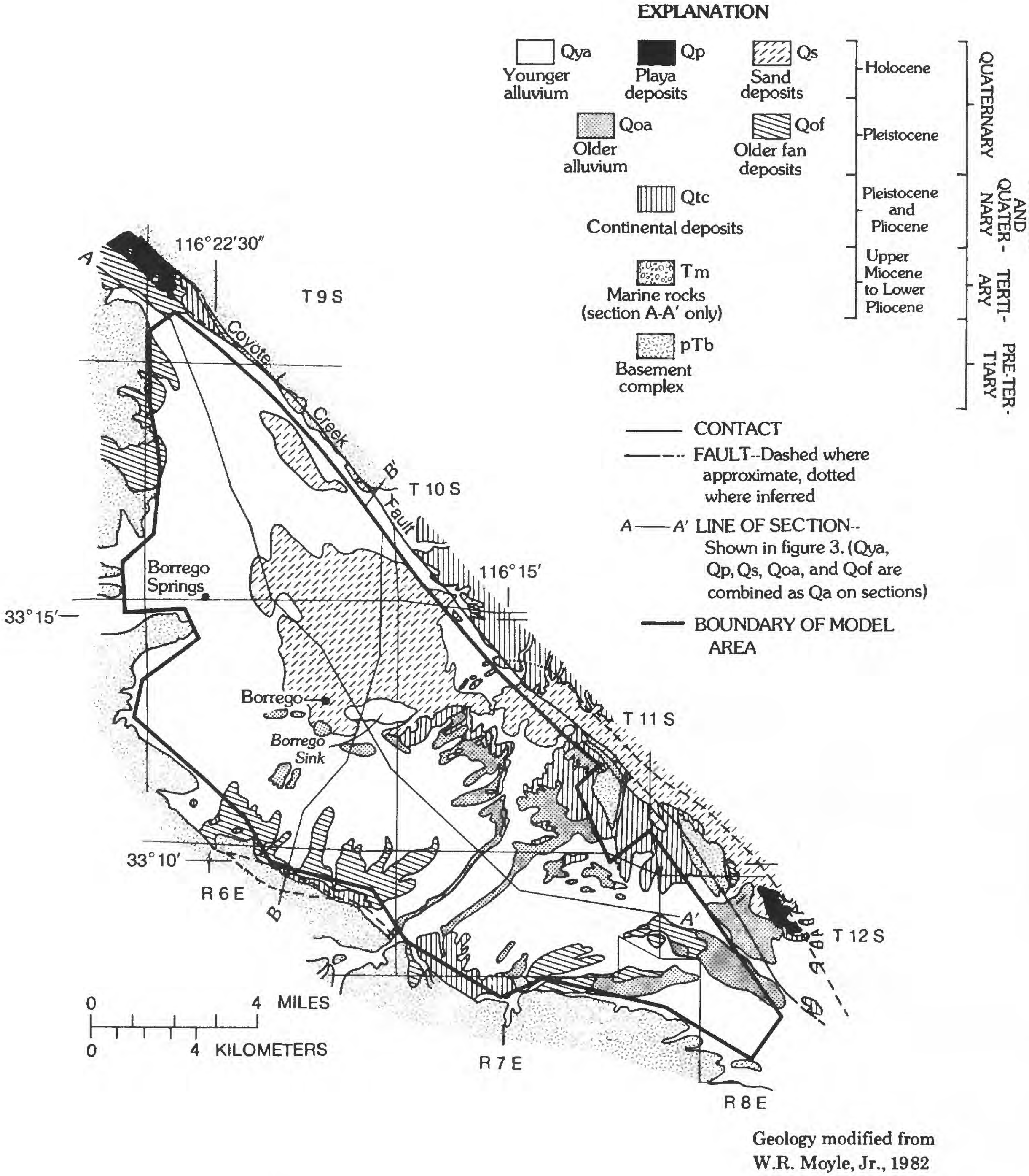


FIGURE 2. – Geology of model area.

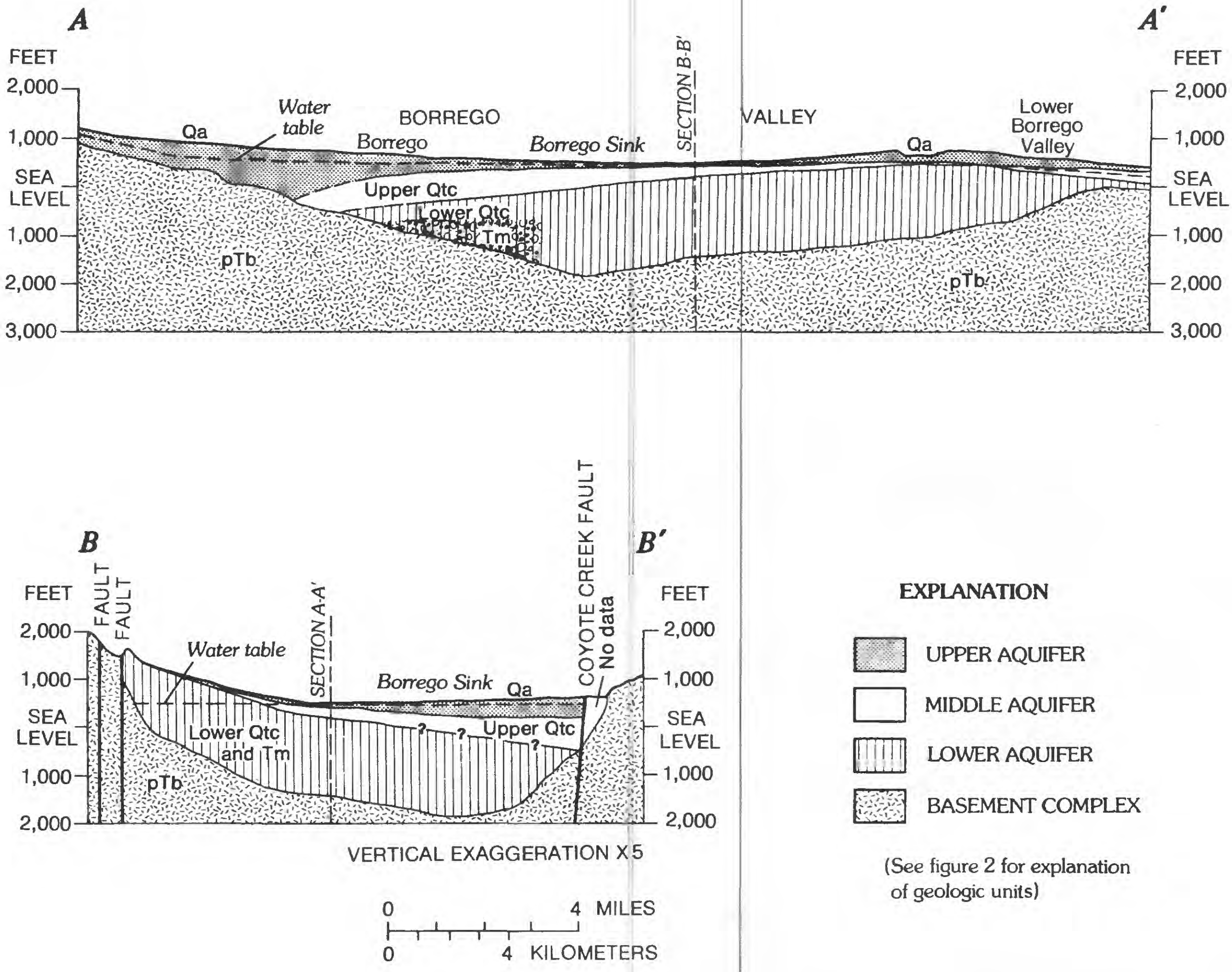


FIGURE 3. – Generalized geologic sections showing extent and thickness of the three aquifers in Borrego and Lower Borrego Valleys.

Natural Recharge and Discharge

Virtually all recharge to the ground-water system in Borrego Valley occurs as infiltration of streamflow, mainly during periods of major surface runoff. Much of the streamflow entering Borrego Valley originates as runoff from igneous and metamorphic rocks in the mountains bordering the valley. On the basis of gaging-station records and a method utilizing channel-geometry measurements at ungaged sites (Hedman, 1970), recharge from streamflow infiltration is estimated to average, over the long term, about 4,800 acre-ft/yr. As summarized in table 1, about 35 percent of the recharge (1,700 acre-ft/yr) occurs along Coyote Creek at the northern end of the valley. About 62 percent of the recharge (3,000 acre-ft/yr) occurs along streams that enter the west side of the valley between Coyote and San Felipe Creeks. It should be noted that although the annual flow of San Felipe Creek averaged about 400 acre-ft/yr during 1959-80 at gaging station 10255700 (see fig. 1), measurements of channel geometry indicate that the stream loses very little water (about 30 acre-ft/yr) in Borrego Valley.

TABLE 1.--Estimated ground-water recharge in Borrego Valley resulting from infiltration of streamflow

Stream	Estimated recharge, in acre-feet per year	Basis of estimate
Coyote Creek................	1,700	1951-80 streamflow records at gaging station 10255800 and channel-geometry measurements
Unnamed streams in Coyote Mountain area.......	100	Channel-geometry measurements
Unnamed streams along west side of Borrego Valley.....	1,700	Do.
Henderson Canyon............	300	Do.
Borrego Palm Creek...........	500	1951-80 streamflow records at gaging station 10255810 and channel-geometry measurements
Hellhole Canyon.............	250	Channel-geometry measurements
Tubb Canyon.................	250	Do.
San Felipe Creek............	30	Do.
Total (rounded)	4,800	

Little, if any, direct infiltration of precipitation recharges the ground-water system in Borrego Valley. Precipitation averages only 3 to 6 inches per year in the valley, and most is lost by evaporation, which averages 60 to 70 inches per year from ponded waters (National Oceanic and Atmospheric Administration, 1982). Precipitation that infiltrates the soil is eventually consumed by natural and cultivated plants that can transpire several feet of water per year if the water is available in the root zone.

Locally, there may be some exchange of water between the three aquifers in the valley and the underlying igneous and metamorphic rocks; however, the volume of water exchanged is believed to be very small. Thus, the contact with the low-permeability igneous and metamorphic rocks is considered a no-flow boundary to the valley ground-water system. Because of water-level differences of 10 to 30 feet on opposite sides of the Coyote Creek fault, the fault is believed to be a barrier to ground-water flow and is considered a no-flow boundary to the valley ground-water system (Moyle, 1982).

Prior to extensive pumping for irrigation, which began in 1946, recharge to the ground-water system was balanced, over long term, by natural discharge. Most of the ground water was discharged by evapotranspiration in the Borrego Sink area. The evapotranspiration cannot be estimated precisely, but it probably averaged 4,000 acre-ft/yr prior to 1946. Also, about 800 acre-ft/yr was discharged, or removed from the valley ground-water system, by subsurface flow into Lower Borrego Valley.

Pumpage

Net pumpage of ground water, which is that part of the pumpage that is actually consumed, ranged from about 1,700 to 13,700 acre-ft/yr during 1946-79 (fig. 4). The estimates of net pumpage are based on maps, aerial photographs, and other land-use information available for 1951, 1954, 1964, 1966, and 1979; on Moyle's (1982) estimates of consumptive-use rates for different irrigated crops; and on population data. Almost all the pumpage during 1946-79 was from the principal (upper) aquifer in northern and central Borrego Valley. Most of the water was used for irrigation of citrus, pasture, a golf course, alfalfa, grapes, date palms, and ornamental trees. Prior to 1946, ground water was used primarily for domestic purposes, and pumpage was probably less than 100 acre-ft/yr. Domestic use of ground water during 1979 is estimated at about 300 acre-ft. Thus, the estimates of net pumpage (fig. 4) mainly reflect changes in both the acreage and types of crops that were irrigated in Borrego Valley.

Since extensive pumping began in 1946, ground-water discharge has exceeded recharge during most years. This imbalance has changed the configuration of the water table in the upper aquifer, lowered water levels in wells as much as 100 feet, and diminished evapotranspiration at Borrego Sink. These changes in the ground-water system were used to calibrate the ground-water flow model, and they are documented in following sections of this report that describe the model.

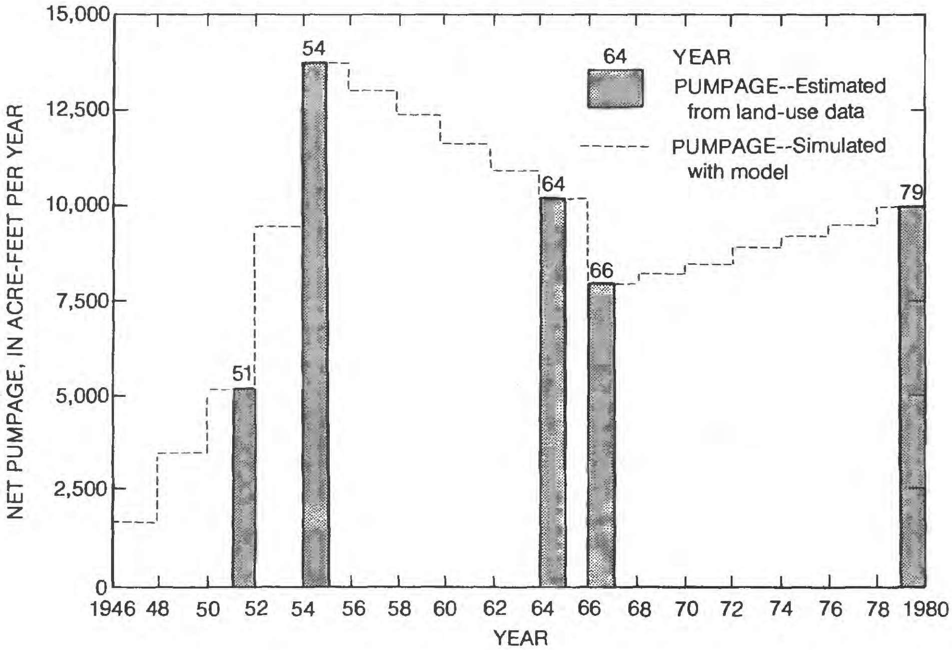


FIGURE 4. — Net ground-water pumpage in Borrego Valley, 1946-79.

GROUND-WATER FLOW MODEL

Numerical Solution

The computer model used for this study utilizes the Galerkin finite-element method for solving the equation of three-dimensional ground-water flow. The reader is referred to Durbin and Berenbrock (1985) for a detailed description of the governing equations and the numerical solution used in the model.

A finite-element model was chosen for use in Borrego Valley because the model grid can be designed to closely approximate the true shape of the three aquifers. The numerical solution of Durbin and Berenbrock's (1985) model also deforms the finite-element grid to account for geometric changes in the ground-water system that result from vertical movement of the water table during transient-state simulations. Also, the numerical solution simulates three-dimensional flow through the multiple-aquifer system; this is in contrast to quasi-three-dimensional models that simulate horizontal flow through aquifers that are connected by leakage through interaquifer confining layers. In Borrego Valley, there are no distinct confining layers between aquifers, and the numerical solution of the Durbin and Berenbrock model more accurately simulates the ground-water system.

Model Description

In order to numerically represent the three-aquifer system of Borrego Valley, it is necessary to divide the system into a finite-element grid, estimate the hydraulic properties of each aquifer, determine the boundary conditions for the system, and estimate the rates and distribution of recharge and discharge.

Finite-Element Grid

The three aquifers in Borrego Valley are represented by a three-dimensional finite-element grid (fig. 5). The grid is assembled, for the most part, from three-high stacks of prismatic elements. The upper, middle, and lower prismatic elements in each stack represent the upper, middle, and lower aquifers. The prismatic elements in each stack are triangular when viewed from above, as shown in figure 5.

The numerical solution of the model fits three tetrahedrons into most prismatic elements as shown in figure 6. To allow flexibility in the construction of the three-dimensional grid, the model also allows the use of prismatic elements with edges of zero height as shown in figure 7. A prismatic element with one zero-height edge contains two tetrahedrons, and an element with two zero-height edges contains one. These special prismatic elements are used to represent aquifers where they taper to zero thickness.

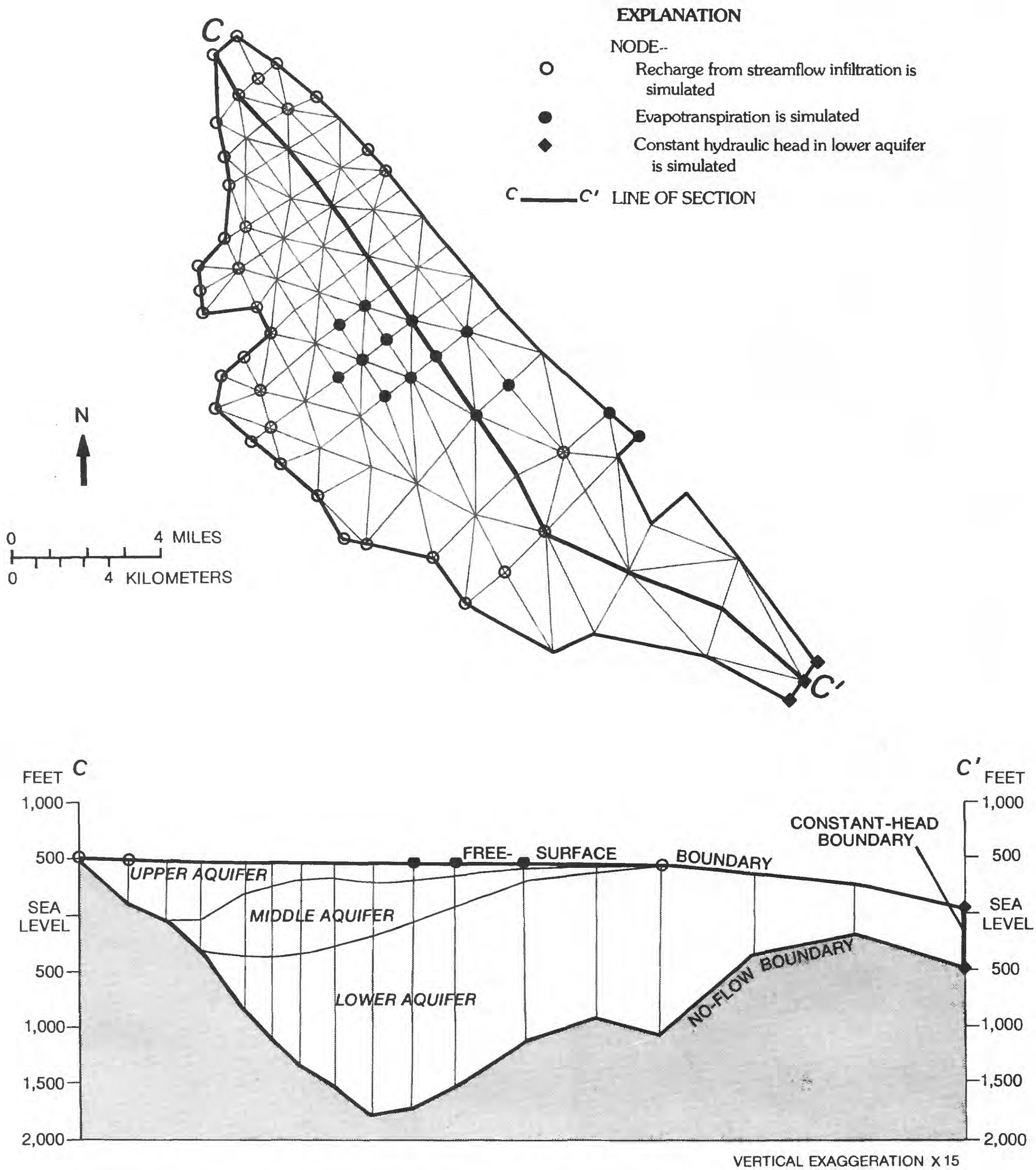


FIGURE 5. – The finite-element model grid and location of nodes where streamflow infiltration, evapotranspiration, and constant hydraulic head are simulated.

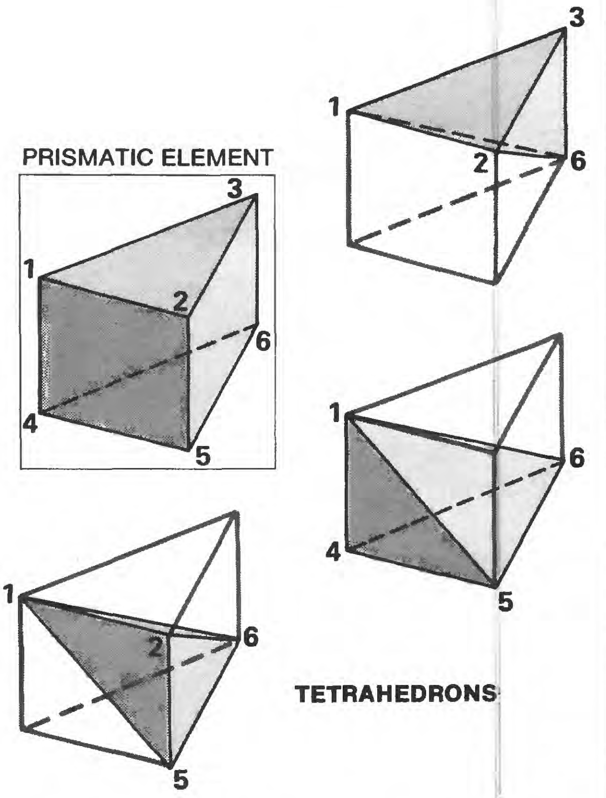


FIGURE 6. – Subdivision of prismatic element into tetrahedrons.

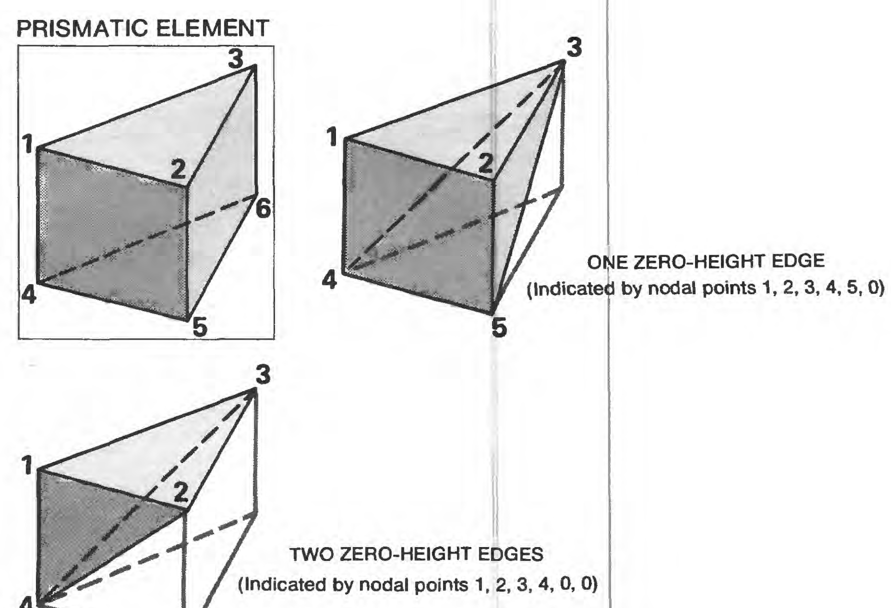


FIGURE 7. – Prismatic element with one or two zero-height edges.

The grid for the Borrego Valley model includes 405 prismatic elements, which are fitted with a total of 1,132 tetrahedrons, and there are 336 nodal points. The dimensions of the prismatic elements range from 2,500 to 18,000 feet horizontally and from 0 to 1,800 feet vertically.

Aquifer Properties

The hydraulic properties of each aquifer are assigned to the appropriate prismatic elements. In turn, the properties are automatically assigned to the tetrahedrons that compose each element. The hydraulic properties include:

1. The hydraulic conductivity for the three principal components of the conductivity tensor (K_{xx}, K_{yy}, and K_{zz});

2. The specific yield (S_y) for those prismatic elements having an upper free-surface boundary (a water table); and

3. The specific storage (S_s) for those prismatic elements not having an upper free-surface boundary.

Initially, Moyle's (1982) estimates of average hydraulic conductivity and storage were assigned to all prismatic elements representing a particular aquifer. At all elements, the vertical hydraulic conductivity (K_{zz}) was assumed to be one-hundredth of the horizontal hydraulic conductivities (K_{xx} and K_{yy}). During the process of model calibration, the hydraulic conductivities and specific yields were adjusted within reasonable limits in order to obtain close agreement between computed and measured hydraulic heads. The hydraulic properties that were assigned to each aquifer following the calibration process are given in table 2. Aquifer thicknesses were defined indirectly by superimposing the model grid on Moyle's (1982) aquifer-thickness maps and assigning an altitude to each node.

TABLE 2.--Hydraulic properties of aquifers used in calibrated model

[Hydraulic properties: K_{xx} and K_{yy}, horizontal conductivities; K_{zz}, vertical hydraulic conductivity; S_s, specific storage; S_y, specific yield]

Hydraulic property	Units	Upper aquifer	Middle aquifer	Lower aquifer
K_{xx}	ft/d	43-81	5.8	1.4
K_{yy}	ft/d	43-81	5.8	1.4
K_{zz}	ft^2/d	0.43-0.81	0.058	0.014
S_s	1/ft	--	0.000001	0.000001
S_y	Percent	14	7	3

Boundary Conditions

Three types of boundary conditions are simulated in the Borrego Valley model. The top surface of the finite-element grid is a free-surface boundary representing the water table. The top surface is free to move vertically in response to imbalances between recharge and discharge during transient-state simulations. Most of the remaining boundary surfaces are no-flow boundaries that represent either the contact between the three aquifers and the underlying basement complex or the ground-water barrier created by the Coyote Creek fault. The southeastern boundary of the model was placed at an arbitrary position in Lower Borrego Valley several miles from the major pumping in Borrego Valley. Because water levels in the lower aquifer at the southeastern boundary are not believed to be affected by pumpage from the upper aquifer in Borrego Valley, constant hydraulic head is simulated at the boundary (fig. 5).

Simulated Recharge and Discharge

Infiltration of streamflow, mainly along the margins of the valley, accounts for virtually all recharge to the three aquifers. The recharge is estimated to average, over the long term, about 4,800 acre-ft/yr (table 1). To simulate the recharge in the model, the water is added through "recharging wells" at the appropriate nodes (fig. 5). During both steady-state and transient-state model simulations, the recharge was simulated at a constant rate, and no attempt was made to simulate seasonal or yearly variations in recharge.

Evapotranspiration is simulated in the model at 14 nodes (fig. 5) in the central part of the valley near Borrego Sink. For modeling purposes, a maximum evapotranspiration rate (Q_{max}) of 4 ft/yr is assumed to occur when the water table is at the land surface, and evapotranspiration is assumed to decrease linearly to zero when the water table declines to 10 feet (D_{max}) below the land surface.

Subsurface flow through the lower aquifer is simulated at the southeastern boundary of the model. This discharge is computed with the model and is dependent on the differences in hydraulic head between the constant-head nodes along the boundary (fig. 5) and the adjacent nodes.

To account for historical ground-water pumpage, discharging wells are simulated at the appropriate nodes, mainly in the northern and central parts of Borrego Valley. Annual-pumpage volumes and the distribution of pumpage were estimated from land-use data. During transient-state calibration of the model, the period 1946-79 was simulated using seventeen 2-year pumping periods (fig. 4). The rates and distribution of pumpage during each 2-year pumping period were assumed to be constant. No pumpage was simulated prior to 1946 when the ground-water system was assumed to be at steady state.

Model Calibration

Model calibration was an educated trial-and-error process of adjusting aquifer properties that were input to the model in order to match computed and measured hydraulic heads. Comparisons between estimated and computed components of the the water budget, such as evapotranspiration and underflow, also were useful in calibrating the model. The initial estimates of aquifer properties were adjusted within limits based on known geologic and hydrologic differences within the ground-water system. Steady-state calibration was used to adjust hydraulic conductivities, and transient-state calibration was used to adjust the specific yields of aquifers.

Steady-State Conditions

An aquifer is considered to be in a steady state when, over the long term, recharge equals discharge. Under these conditions, there is no long-term change in hydraulic heads and in ground-water storage, although small changes may occur from year to year. During 1945, ground-water levels in Borrego Valley remained fairly constant, and they are believed to be fairly representative of steady-state conditions. Because there probably was less than 100 acre-ft of water pumped during 1945, hydraulic heads in the three aquifers were mainly dependent on the location and rates of natural recharge and discharge.

For the steady-state calibration, the estimated long-term average recharge from streamflow infiltration (4,800 acre-ft/yr) was used; evapotranspiration was simulated at the appropriate nodes; and Moyle's (1982) estimated average hydraulic conductivities of 50, 5, and 1 ft/d were used initially for the upper, middle, and lower aquifers. In order to obtain a reasonable match between measured and computed hydraulic heads, hydraulic conductivity of the upper (principal) aquifer was varied from 43 to 81 ft/d, and hydraulic conductivities of the middle and lower aquifers were raised slightly to 5.8 and 1.4 ft/d.

Water-level measurements and estimates using Moyle's (1982) water-level contour map for 1945 allowed comparison with computed hydraulic heads at 73 nodes. After final adjustments to the hydraulic conductivities, the difference between the measured/estimated heads and those computed at the 73 nodes ranged from -2.2 to 11.6 feet. The root-mean-square deviation was 3.7 feet. The root-mean-square deviation, which is an indication of the closeness of the match between measured/estimated heads and those calculated with the model, was calculated using the equation:

$$R = \sqrt{\frac{\sum_{i=1}^{n} (M-C)^2}{n}},$$

where

R = root-mean-square deviation, in feet,
M = measured/estimated water level, in feet,
C = computed hydraulic head, in feet; and
n = total number of water-level measurements/estimates.

The hydraulic-head distribution resulting from the steady-state calibration is shown in figure 8. The map in figure 8 shows the computed altitude of the water table, and the cross section in figure 8 shows the computed vertical distribution of hydraulic head in the three aquifers. The lines of equal hydraulic head in the cross section indicate that there was little computed difference in hydraulic head with depth in the system, and ground water was simulated as moving mainly horizontally through the three aquifers.

Estimated transmissivity of the principal (upper) aquifer resulting from steady-state calibration of the model is shown in figure 9. The transmissivity in figure 9 is the product of the final adjusted hydraulic conductivities input to the model and the saturated thicknesses of the aquifer. The estimated transmissivity ranged from zero at the edges of the aquifer to more than 24,000 ft^2/d where the aquifer has a maximum thickness of about 600 feet.

The ground-water budget computed for steady-state conditions is given in table 3. The long-term average rate of streamflow infiltration (4,800 acre-ft/yr) input to the model is balanced by computed evapotranspiration (3,900 acre-ft/yr) near Borrego Sink and computed subsurface outflow (930 acre-ft/yr) at the southeastern boundary of the model. Error of closure for the computed steady-state water budget was 0.9 percent, which is reasonable.

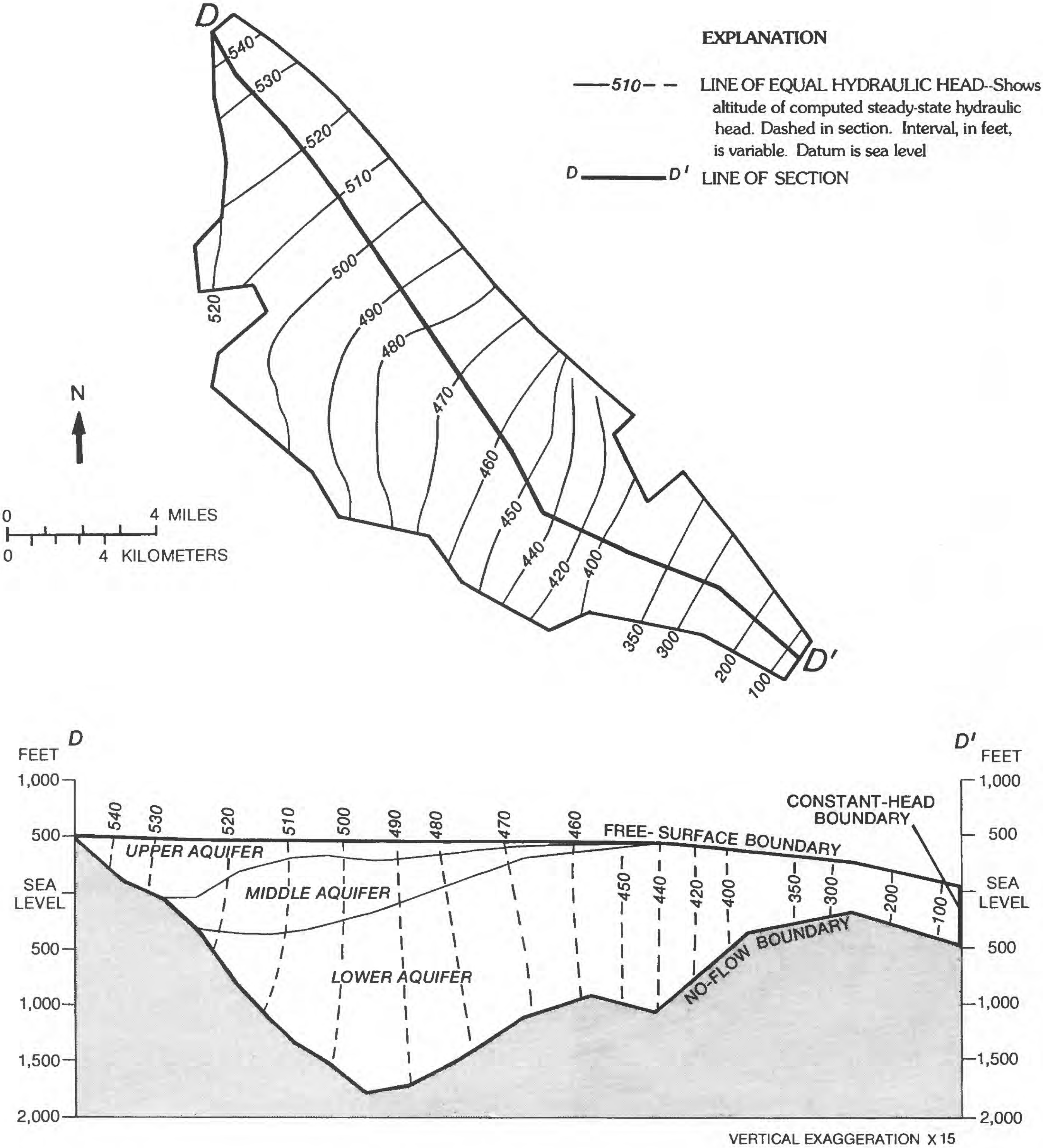


FIGURE 8. — Computed steady-state (1945) hydraulic head.

TABLE 3.--Ground-water budgets computed for steady-state conditions (1945) and for selected years during transient-state conditions (1946-79)

[Values are in acre-feet per year. Positive values indicate additions to the ground-water system and negative values indicate removals]

Water-budget component	Steady state	Transient state			
	1945	1953	1963	1971	1979
Recharge from streams	4,800	4,800	4,800	4,800	4,800
Discharge					
Net pumpage	0	-9,400	-10,900	-8,600	-9,900
Evapotranspiration	-3,900	-2,840	-800	-460	-200
Subsurface outflow at southeast boundary	-930	-930	-930	-930	-930
Change in storage	0	-8,400	-7,800	-5,200	-6,200

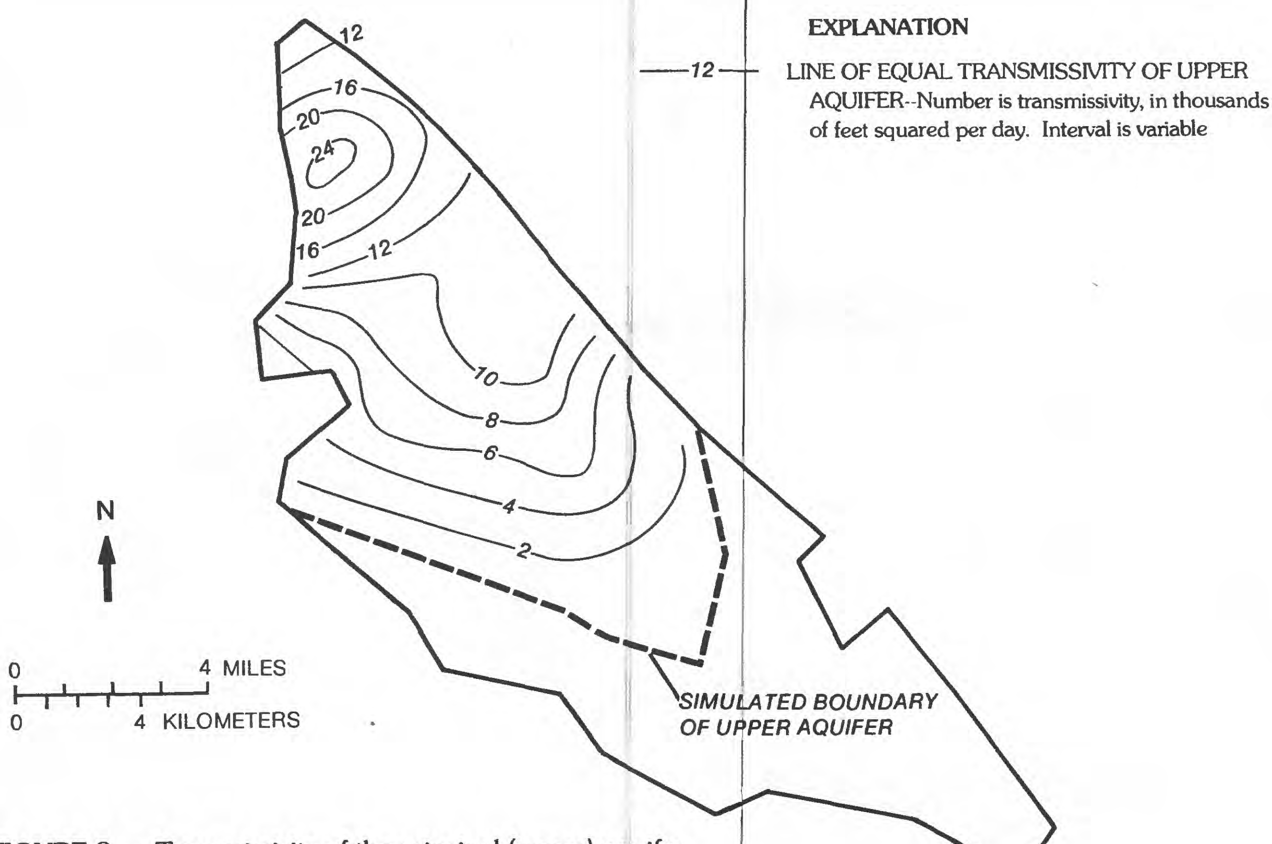


FIGURE 9. – Transmissivity of the principal (upper) aquifer in Borrego Valley estimated from model calibration.

Transient-State Conditions

Transient state is a condition whereby hydraulic heads and ground-water storage change with time in response to imbalances between recharge and discharge. In Borrego Valley, water levels in wells changed dramatically during 1946-79 mainly in response to pumping for irrigation. To simulate transient-state conditions, the period 1946-79 was divided into 17 time steps of 2 years each. During each 2-year time step, net pumpage was assumed to be constant (fig. 4).

Recharge from streamflow infiltration varies from year to year; however, available data did not allow the recharge to be varied during the transient-state calibration. Instead, streamflow infiltration was simulated at a constant rate of 4,800 acre-ft/yr, which is the estimated long-term average. In addition, the evapotranspiration variables Q_{max} and D_{max} were assumed to remain constant.

During the transient-state calibration, hydraulic conductivities resulting from the steady-state calibration were held constant, and a uniform specific storage of 0.000001 was assigned to all prismatic elements of the model not having an upper free-surface boundary (that is, all confined parts of aquifers). The specific yield was varied, within reasonable limits, for all unconfined parts of aquifers until there was a reasonable match between measured/estimated hydraulic heads and those computed with the model. Specific yields of 14, 7, and 3 percent for the upper, middle, and lower aquifers (table 2) produced the best match between the computed and measured/estimated hydraulic heads. Although the specific yield of water-bearing materials in each aquifer varies, the uniform values of specific yield do adequately represent each aquifer as a whole.

The computed distribution of hydraulic head at the end of 1979 is shown in figure 10, along with the 10 nodes where historic water-level records from nearby wells allowed calibration of the model during transient state. After adjustments to aquifer specific yields, there was acceptable agreement between measured/estimated heads and those computed using the model. (See fig. 11.) The difference between measured/estimated heads during 1946-79 and the calculated heads ranged from -16 to 18 feet; the root-mean-square deviation was 8 feet.

The computed ground-water budgets for selected years during 1946-79 are given in table 3. As is evident from table 3 and figure 12, pumpage was compensated, in part, by a rapid decrease in the rate of evapotranspiration. The computed evapotranspiration decreased to a rate of 2,840 acre-ft/yr by 1953 and to 200 acre-ft/yr by 1979. But more significantly, the pumpage was mainly compensated by a decrease in the amount of ground water in storage. For example, net pumpage during 1953 was estimated at 9,400 acre-ft/yr, and the volume of ground water in storage decreased at a rate of about 8,400 acre-ft/yr. Computed heads near the southeastern boundary of the model changed very little during 1945-79, and the computed subsurface outflow remained steady at a rate of about 930 acre-ft/yr. Error of closure for each computed transient-state water budget was less than 0.4 percent.

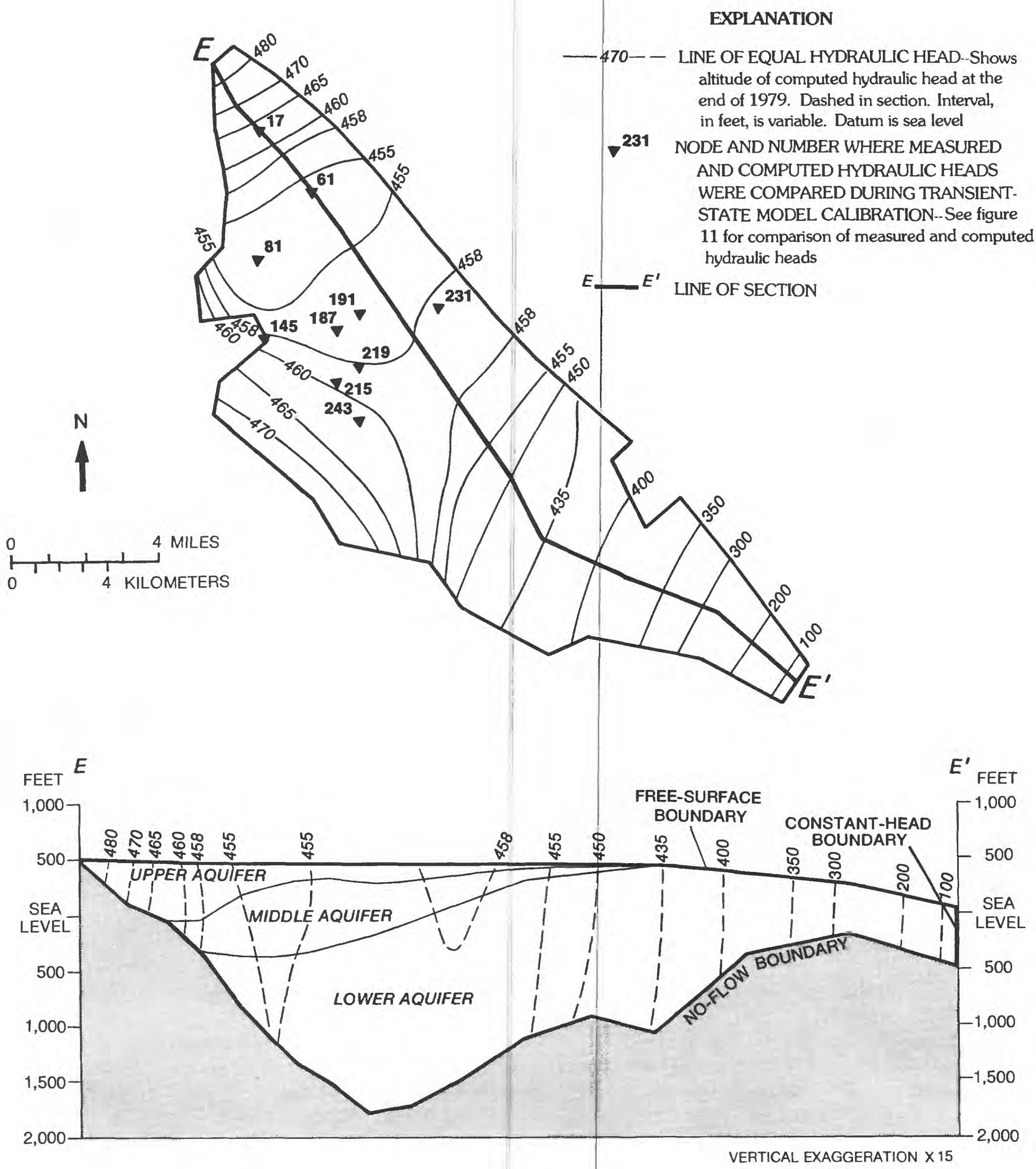


FIGURE 10. — Computed hydraulic head at the end of 1979 and location of nodes where measured water levels were used for the transient-state model calibration.

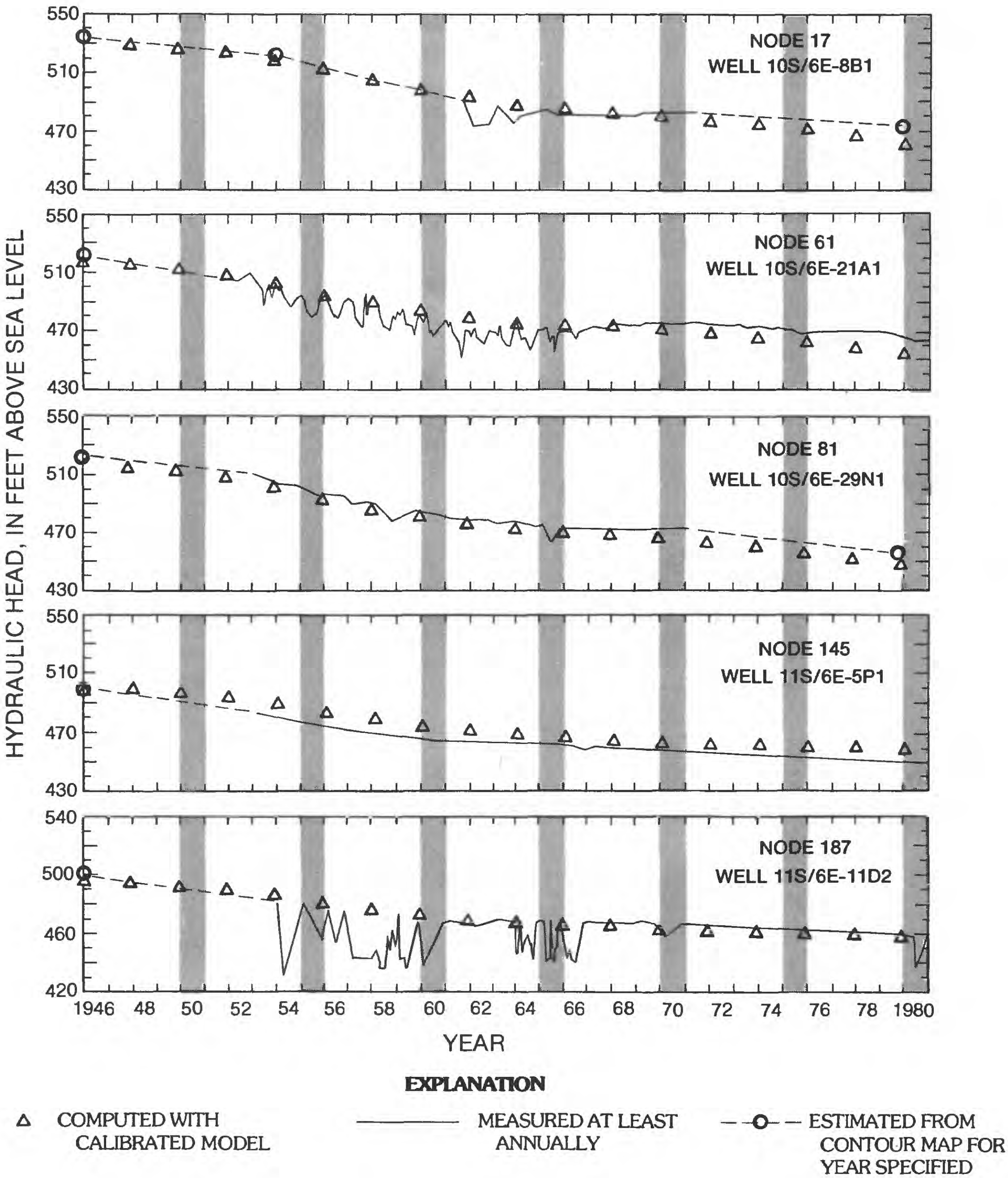


FIGURE 11. – Measured, estimated, and computed hydraulic heads at selected nodes, 1945-79.

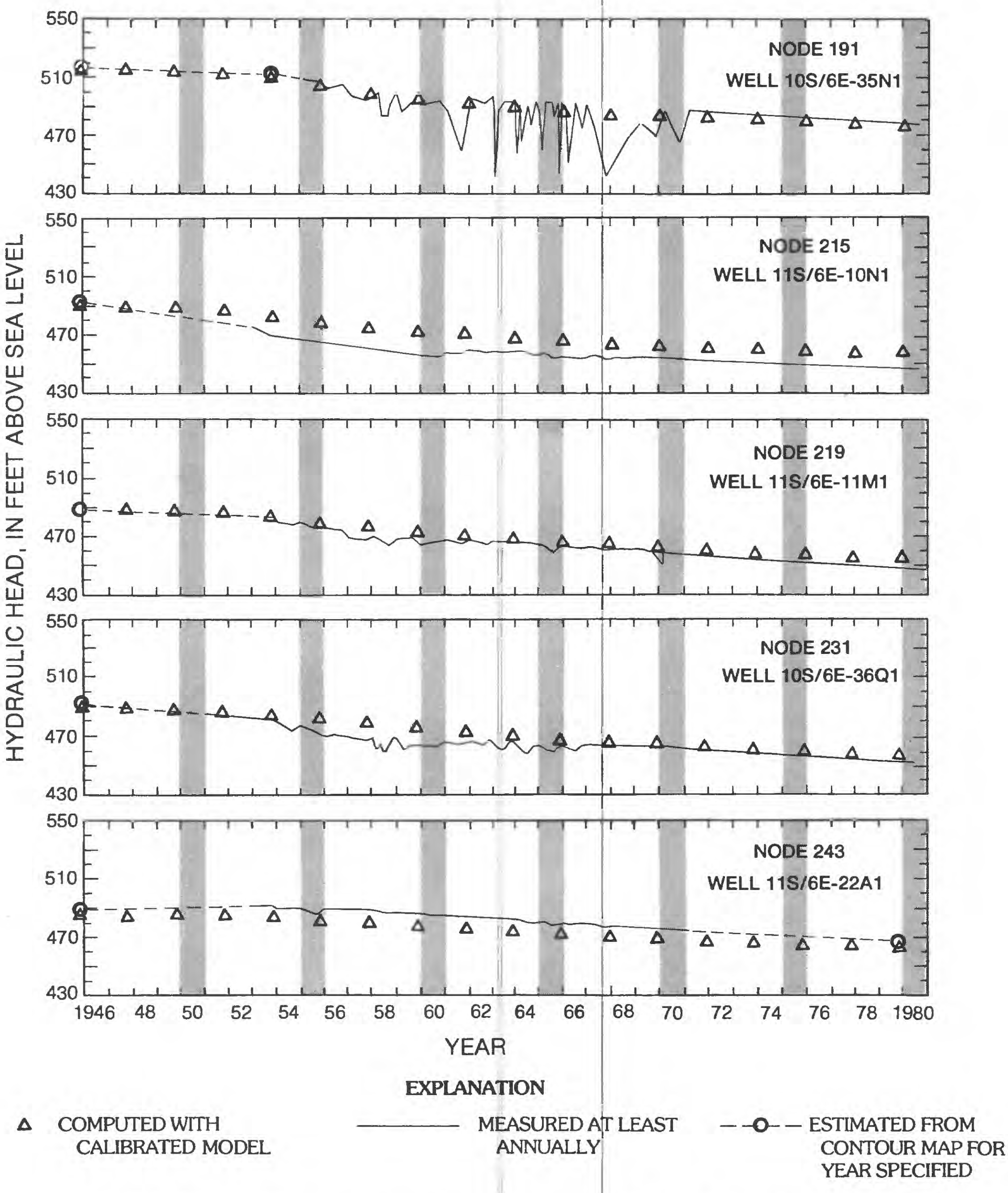


FIGURE 11. – Measured, estimated, and computed hydraulic heads at selected nodes, 1945-79--Continued.

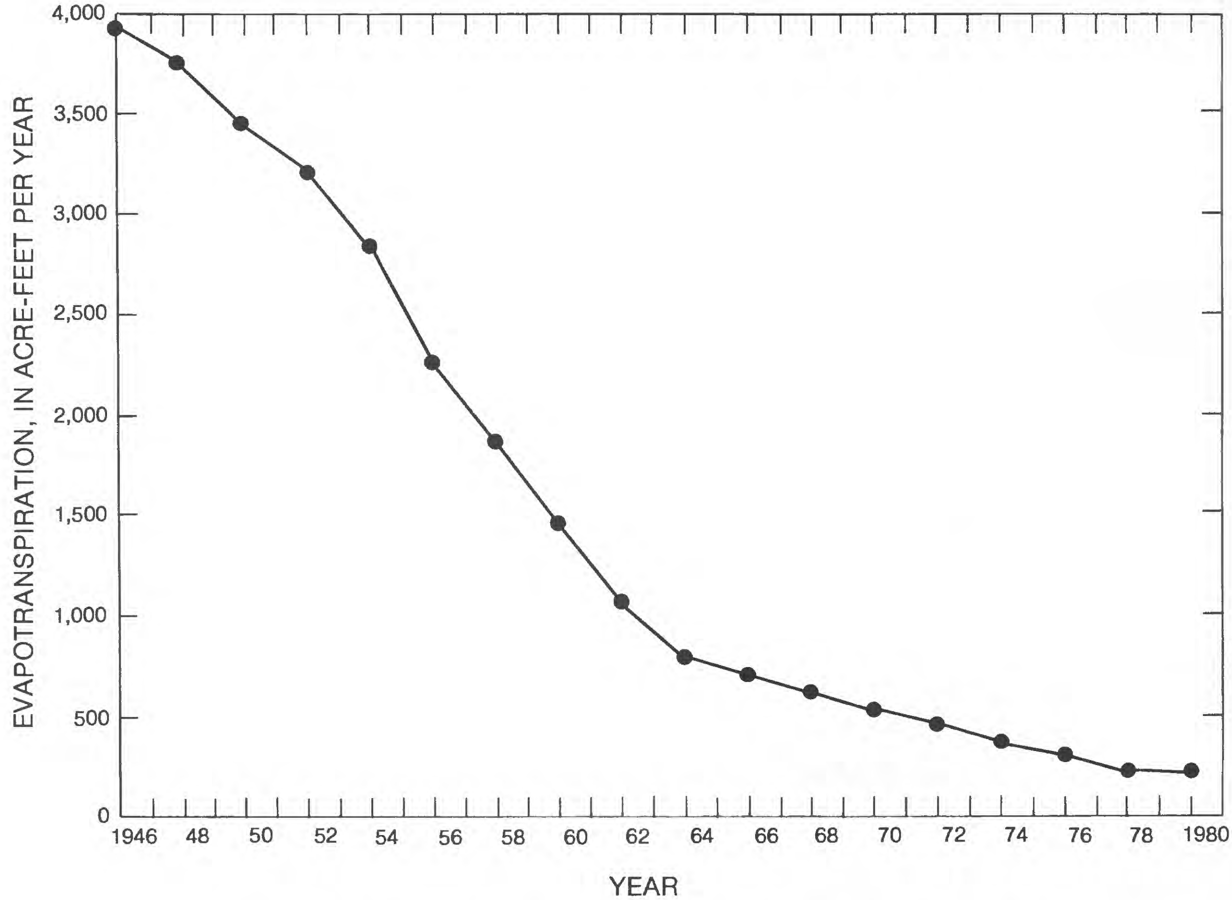


FIGURE 12. – Computed evapotranspiration of ground water, 1945-79.

Model Sensitivity

Transient-state simulations for the period 1946-79 were used to determine the sensitivity of the model to changes in the hydraulic properties of the upper aquifer, in recharge, and in net pumpage. The sensitivity analysis was accomplished in a series of separate simulations by holding all input parameters constant, except for the one being studied. The parameter being studied was varied over a wide range of values, and the effects of each change were determined by computing the root-mean-square deviation for hydraulic head for each simulation.

Plots of the root-mean-square deviation versus the change factor for each parameter studied are shown in figure 13. When the change factor is 1, the parameter is unchanged from the final calibration value. For example, when the vertical hydraulic conductivities of the upper aquifer resulting from final model calibration are increased by a factor of 100 (change factor 100), the root-mean-square deviation increases from 8 to 10 feet. It should be pointed out that the range of values used in the sensitivity analysis is for illustration only; frequently the range of values is far beyond any reasonable estimate of parameter variability.

The sensitivity analysis indicates that the model during transient-state simulations is most sensitive to changes in specific yield of the upper aquifer, in net pumpage, and in recharge. Small errors in simulating these input parameters can have a significant effect on computed heads during transient-state simulations.

The model during transient-state simulations is least sensitive to changes in horizontal and vertical hydraulic conductivities of the upper aquifer. The hydraulic conductivities can be varied over a wide range without significantly affecting the computed hydraulic heads during transient-state simulations.

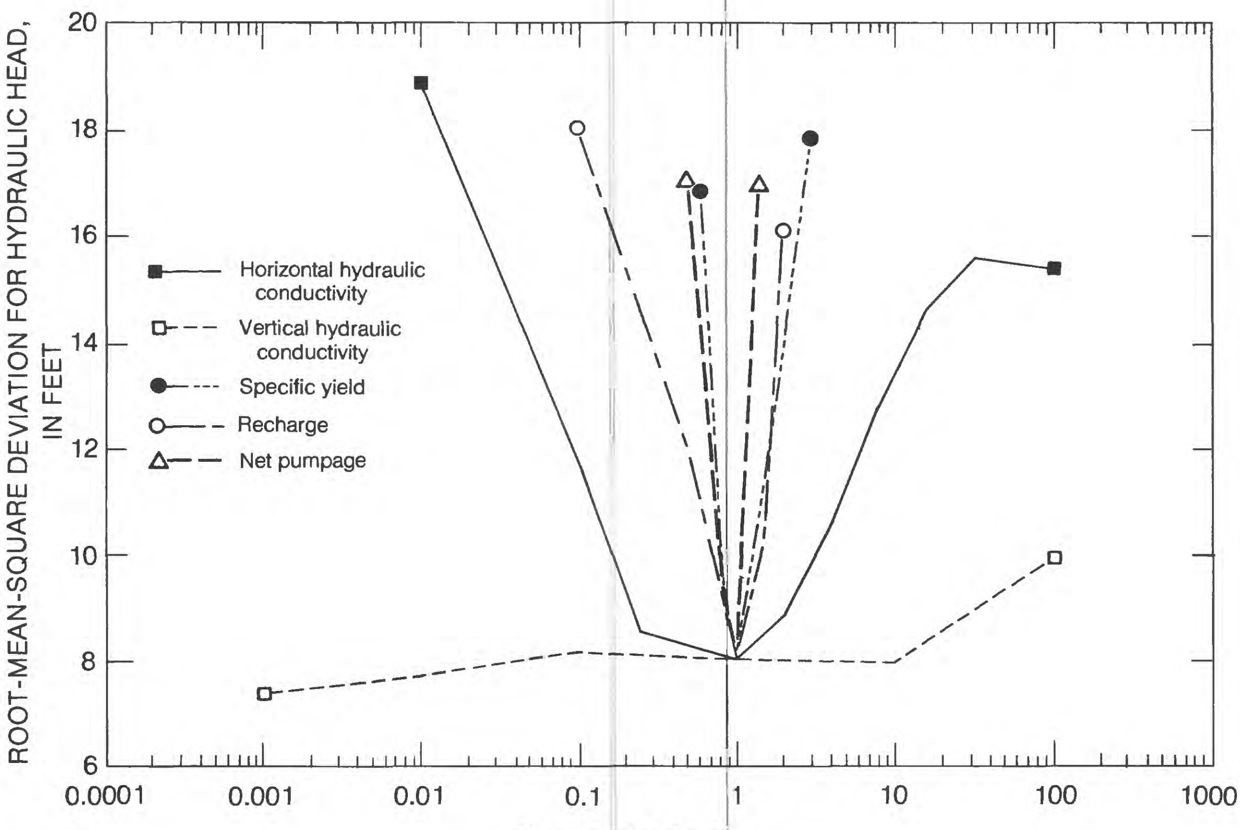


FIGURE 13. — Sensitivity of the model during transient state (1946-79) to hydraulic properties of the principal (upper) aquifer, to recharge, and to net pumpage.

Model Assumptions and Limitations

Construction and calibration of a ground-water flow model requires some simplifying assumptions concerning the recharge, discharge, and hydraulic properties of aquifers. Some of the simplifying assumptions for the Borrego Valley model include:

1. Recharge occurs at a constant rate.
2. Net pumpage occurs at a constant rate during each 2-year time step.
3. Changes in ground-water storage occur instantaneously with changes in hydraulic head.
4. The aquifers are isotropic with respect to horizontal hydraulic conductivity, and vertical hydraulic conductivities are one-hundredth of the horizontal conductivities.
5. The aquifers are isotropic with respect to storage properties.

Because a constant rate of recharge and constant rates of pumpage for periods of 2 years are assumed, the hydrographs of computed hydraulic heads (fig. 11) do not reflect the seasonal and yearly variations that actually occur. Also, instantaneous changes in ground-water storage in response to changes in hydraulic head do not account for delayed yields from storage in the unconfined upper aquifer or the time required for recharge water to move through the unsaturated zone and reach the water table. However, the errors introduced by these assumptions are minimal when considering long-term water-level trends, such as during the transient-state calibration period of 1946-79.

The three aquifers of Borrego Valley are composed of layered deposits of varying lithology, sorting, and consolidation, and they do not have isotropic horizontal hydraulic conductivities and storage properties as assumed for the model. However, when large blocks of each aquifer (each prismatic element) and the aquifers as a whole are considered, they act as if they have isotropic storage properties and isotropic horizontal hydraulic conductivities.

Because of layering of sediments in each aquifer (interbedded sand, silt, and clay beds), vertical hydraulic conductivities are significantly less than horizontal hydraulic conductivities. Aquifer-test data were not available to estimate vertical hydraulic conductivities, and it was assumed that they were one-hundredth of the horizontal hydraulic conductivities assigned to each prismatic element. As indicated in figure 13, simulated heads are virtually insensitive to changes of several orders of magnitude in the vertical hydraulic conductivity of the upper aquifer. Thus, the assumed vertical hydraulic conductivities adequately represent the real ground-water system.

Despite the simplifying assumptions, the computer model provides the most realistic way to analyze the effects of pumpage on the ground-water system. The alternative approach, using an analytical method of analysis, would require more simplifying assumptions than those associated with the computer model. Because the model was calibrated mainly with water-level data and historical pumpage from the principal (upper) aquifer, it can be used with the most confidence to predict hydraulic-head changes in response to assumed future pumpages from the upper aquifer. Few historical hydraulic-head data for the middle and lower aquifers were available to calibrate the model. Thus, predictive simulations in which large quantities of water are pumped from the middle and lower aquifers can be used to predict general water-level trends, but the calculated hydraulic heads and fluxes should be considered order-of-magnitude approximations.

SUMMARY

A three-dimensional finite-element digital model of the three-aquifer system in Borrego Valley was constructed and calibrated. Most of the hydrologic data needed for the model were obtained from phase 1 of the study (Moyle, 1982). In addition, channel-geometry measurements and records from gaging stations were used to estimate the long-term average rate of recharge from infiltration of streamflow. The rates and distribution of net pumpage were estimated from land-use information and estimated consumptive use of various irrigated crops.

Water-level measurements in 1945, prior to extensive pumping in the valley, were used to calibrate the model to steady-state conditions. During the steady-state calibration, hydraulic conductivities of the three aquifers were varied within reasonable limits in order to match computed and measured/estimated hydraulic heads. After final adjustments to the hydraulic conductivities, the difference between the measured/estimated heads and those computed with the model ranged from -2.2 to 11.6 feet. During steady state, the long-term average rate of recharge from streamflow infiltration (4,800 acre-ft/yr) that was input to the model was balanced by computed evapotranspiration (3,900 acre-ft/yr) and subsurface outflow at the southeastern boundary of the model (930 acre-ft/yr).

To calibrate the model to transient-state conditions, the period 1946-79 was divided into seventeen 2-year time steps. The estimated net pumpage was simulated at the appropriate nodes for each 2-year time step. The specific yield was varied within reasonable limits at each prismatic element representing an unconfined part of an aquifer until there was a reasonable match between measured/estimated heads and heads computed with the model. Specific yields of 14, 7, and 3 percent for the upper, middle, and lower aquifers produced the best match. At the end of transient-state calibration, the difference between measured/estimated heads during 1946-79 and those computed with the model ranged from -16 to 18 feet; the root-mean-square deviation was 8 feet. During transient state, the long-term average recharge rate (4,800 acre-ft/yr) was input to the model at the appropriate nodes. Net pumpage, which ranged from about 1,700 to 13,700 acre-ft/yr during 1946-79, was compensated by declines in both the computed evapotranspiration and the amount of ground water in storage. The contribution from aquifer storage has exceeded the combined contribution from recharge and decreased evapotranspiration since 1953.

The calibrated model can be used to analyze historical and future effects of pumping on the ground-water system. As a predictive tool, it can be used with the most confidence to analyze hydraulic-head changes in response to assumed future pumpage from the upper (principal) aquifer.

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